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CONCERNING THE SIMILITUDE OF MOLECULAR
TRANSFER PROCESSES IN RARIFIED GASES

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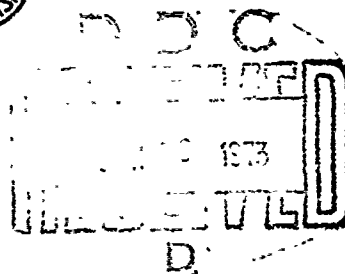
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by

G. F. Shaykhiyev



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III

CONCERNING THE SIMILITUDE OF MOLECULAR TRANSFER PROCESSES IN RARIFIED GASES

G. F. Shaykhiyev

Earlier [1] a method was presented for the calculation of derived integrals of collisions for processes of mass transfer which makes it possible to use equations obtained in a strict kinetic theory for determining the coefficients of self-diffusion and diffusion of various gas systems.

In the present article it is shown that the expression for the derived integral of collisions given in work [1] can be obtained from more general presentations and for all processes of molecular transfer.

As is known, the rate of change of entropy in a closed system is conditioned by macroscopic processes of thermal conductivity, internal friction, and diffusion. This equation has the form [3]:

$$T\rho \frac{ds}{dt} = -\vec{J}_s \frac{\text{grad } dT}{T} - \text{div } \vec{J}_s \text{grad } T - \vec{J}_k \text{grad } \mu_k - \Pi : \text{grad } \vec{w}. \quad (1)$$

Expression (1) in conjunction with the relationships of Onsager is usually used for analyzing the phenomena of transfer. We will use it for obtaining the conditions of similitude for processes of molecular transfer.

If the irreversible flows $\vec{I}_s, \vec{I}_k, \vec{I}$ are expressed through the laws of Fourier, Fick, and Newton [3], then after certain simple transformations it is possible to obtain from [1] the following differential equation for a single-component gas for an isotropic system in a unidimensional case:

$$T\rho \frac{ds}{dt} = \lambda \frac{\partial^2 T}{\partial x^2} + \frac{\lambda}{T} \left(\frac{dt}{dx} \right)^2 + \eta \left(\frac{\partial w}{\partial x} \right)^2 + \frac{DP}{\rho_k^2} \left(\frac{\partial \rho_k}{\partial x} \right)^2. \quad (2)$$

The investigation of this expression separately for each type of transfer for invariance in the case of a similar transformation gives the following criteria of similitude:

$$L_\lambda = \frac{\rho S x^2}{t \eta}. \quad (3)$$

$$L_\eta = \frac{T \rho S x^2}{t \eta \alpha^2}. \quad (4)$$

$$L_D = \frac{T S x \rho^2}{t D P}. \quad (5)$$

At a distance of the length of free path in the analyses of processes of molecular transfer of heat, pulse, and mass [3-5] the change in the parameters of state is usually considered small.

This makes it possible to use a quasi-equilibrium examination of the elements of volumes which are commensurate with the length of free path of molecules, and for the characteristics of their condition to take the equilibrium parameters P, V, T, S. Therefore in equations (3)-(5) x and t have the meaning of length and time of the free path. The latter for rarified gases which satisfy the conditions of solution of the Boltzman equation can be written:

$$x = e = \frac{m}{\sqrt{2\pi\sigma^2}}. \quad (6)$$

$$t = \tau_0 = \frac{m}{4\pi\sigma^2} \sqrt{\frac{M}{\pi RT}}. \quad (7)$$

Then with a calculation of (6)-(7) the criteria of similitude (3)-(5) are reduced to the form:

$$L_\lambda = \frac{2}{N} \sqrt{\frac{R}{\pi}} \cdot \frac{1}{\lambda} \cdot \sqrt{\frac{T}{M}} \cdot \frac{S_p}{\pi\sigma^2}. \quad (8)$$

$$L_\eta = \frac{1}{4N} \cdot \sqrt{\frac{\pi}{R}} \cdot \frac{1}{\eta} \cdot \sqrt{MT} \cdot \frac{S_p}{\pi\sigma^2}. \quad (9)$$

$$L_D = \frac{2}{N} \sqrt{\frac{R}{\pi}} \cdot \frac{1}{DP} \sqrt{\frac{T^3}{M}} \cdot \frac{S_p}{\pi\sigma^2} \quad (10)$$

The conditions of similitude of the type (8)-(10) contain in an evident form the kinetic characteristics of the system. Therefore they can be used for calculating the coefficients of transfer.

Calculations made for inert gases showed that criteria L_λ , L_η , L_D are constant and do not depend on the parameters of state at high temperatures. This is valid for systems with a weak interaction, which we are examining. The evaluation of constants in (8)-(10) using the data of L_λ , L_η , L_D , σ shows that they are close to the values

$$\frac{25}{32} \sqrt{\frac{R}{\pi}} \cdot \frac{C_v}{N} = \frac{2}{N} \sqrt{\frac{R}{\pi}} \cdot \frac{\sigma^2}{L_\lambda};$$

$$\frac{5}{16N} \sqrt{\frac{R}{\pi}} = \frac{1}{4N} \sqrt{\frac{\pi}{R}} \cdot \frac{\sigma^2}{L_\eta}; \quad \frac{3}{8N} \sqrt{\frac{R}{\pi}} \cdot \frac{\sigma^2}{L_D},$$

known from the equations of the strict kinetic theory of gases. With a calculation of equations for the calculation of derived integrals of collisions obtained in [1, 6, 7] the coefficients of transfer of rarified gases can be expressed in the form:

$$\lambda = \frac{25}{32} \sqrt{\frac{R}{\pi}} \cdot \frac{C_v}{N} \cdot \frac{\sqrt{\frac{T}{M}}}{\sigma^2 \Omega_\lambda^*(S)}. \quad (11)$$

$$\eta = \frac{5}{16N} \sqrt{\frac{R}{\pi}} \cdot \frac{\sqrt{TM}}{\sigma^2 \Omega_\eta^*(S)}. \quad (12)$$

$$D = \frac{3}{8N} \sqrt{\frac{R}{\pi}} \cdot \frac{\sqrt{\frac{T}{M}}}{P \sigma^2 \Omega_D^*(S)}. \quad (13)$$

Thus the results of the analysis of equation (1) by the method of the theory of similitude makes it possible to reproduce the relationships for the calculation of the coefficients of transfer which are obtained in a strict kinetic theory of gases from the solution of the Boltzman equation. On the basis of previous calculations [1, 6, 7] it can be noted that equations (11)-(13) are suitable for the calculation of the coefficients of transfer of a wide circle of substances. In a general case the criteria L_λ , L_η , L_D can be used for analyzing the phenomena of transfer of any states of substances, but for this it is necessary to evaluate the length and time of free path in (3)-(5).

Conditional Designations

T - temperature, P - pressure, ρ - density, M - molecular weight, R - gas constant, S_μ - absolute molar entropy, C_v - thermal capacity at a constant volume, μ_k - chemical potential of the k-th component of the mixture, λ , η , D - coefficients of thermal conductivity, viscosity, and self-diffusion respectively; ω - thermal velocity, σ - diameter of interaction, $\Omega_\lambda^*(S)$, $\Omega_\eta^*(S)$, $\Omega_D^*(S)$ - derived integrals of collisions of the transfer of heat, pulse, and mass.

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